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The Conclusion from One Million Tonnes of Experience in Galvanizing Steel – LMAC is not a Primary Instigator of Cracking

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Abstract

In the period 2000-2006 occasional instances of serious service cracking in galvanized structural steelwork were detected. At the time it was suggested that the cracks had occurred during the galvanizing process, been covered up by the zinc coating and then opened up during service. Several significant European-wide research projects were initiated to identify and understand the mechanisms that control LMAC during hot dip galvanizing. However, experience in the UK has shown that the frequency of cracking of structural steel during galvanizing is very low, and that when it does occur it is almost invariably due to known factors that influence the propensity for weld cracking and that are also influential during the galvanizing process, e.g. distortion cracking, hydrogen embrittlement and strain age embrittlement. This paper reports, for the first time, the results of a systematic attempt to examine, identify and record the possible presence and type of any pre-existing defects present in some one million tonnes of steelwork prior to the galvanizing process and their contribution to any cracking observed after galvanizing.

Keywords: Galvanizing; structural steelwork; cracking; industrial experience.

1. Introduction

In the period 2000-2006, as noted in reference [1], occasional instances of serious cracking in galvanized structural steelwork were detected. At the time, it was suggested that the cracks had occurred during the galvanizing process and been either filled with, or covered up by, the zinc coating and then subsequently opened up under loading. However, there is also a possibility that crack initiation had occurred as a result of fabrication prior to galvanizing and that this had not been detected until a larger crack existed. Reference [1] notes that these observations were coincident with the fabrication of steel components with larger sizes, characterised by greater plate thickness, higher strength steel alloys, new zinc alloy compositions in the galvanizing bath, and various dipping processes. In particular, the use of higher concentrations of tin in the melt was identified as a factor in the reported cracking, in combination with other elements intended to obtain thinner zinc coats with a better surface appearance. Although tin had been present at varying levels in European general galvanising for many years because of the common use of zinc that had been recycled from roofing material with soldered joints, it had not previously been associated with elevated risks of cracking when galvanizing steels. The levels of tin identified as present in these new instances were significantly higher than had previously been used in established practice. Consequently, it became a focus of attention.

Such cracks were attributed to the phenomenon of liquid metal assisted cracking (LMAC). Consequently, major investigations were initiated and the extensive work done by RWTH Aachen and other universities was described in a report produced by the EU Joint Research Committee (JRC) [1]. This was similar to the investigations previously carried out in Japan and later published as the Tomoe Report in 2001 [2]. This identified the possibility of zinc-related LMAC and looked at factors in product design, steel analysis and quality, welding and galvanizing techniques that influenced cracking, particularly in welds and Heat Affected Zones (HAZ). However, it did not identify the galvanizing bath constituents as potentially causal.

A major European research project (FAMEGA – Failure Mechanisms during Galvanizing [3]) was also initiated to identify and understand the mechanisms that control LMAC during hot dip galvanizing. This work was intended to enable galvanizing of higher strength steel components and fabrications without risk of cracking. The conclusions section of reference [3] provided recommendations for guidelines for the avoidance of LMAC during hot dip galvanizing of steel structural components. Based on the results obtained from these investigations, the Deutsche Ausschluß für Stahlbau (DAST), produced Richtlinie R022 that set guidelines for galvanizing structural steelwork [4]. The Richtlinie R022 guideline [4] is the basis for current German practice in hot dip galvanizing of structural steelwork and has stricter limits in terms of tin content (0.10%) in the galvanizing bath than the 0.30% limit specified in the guidance issued by the British Constructional Steelwork Association and Galvanizers Association (BCSA-GA) in 2005 [5].

However, it is worth noting that the higher tin limit of 0.30% is supported by the results obtained in recent work published by Carpio et al [6] who propose a model for the failure micromechanisms of structural steels during hot-dip galvanizing, and conclude that *“Sn and Bi must be eliminated or at least reduced to less than 0.1% of Bi and 0.3% Sn in order to avoid failures. (This is the recommendation given by this model, 0.5% of Sn, plus a security factor). Lower Sn and Bi contents increase incubation time to failure, and make it easier to suppress cracking.”*

Feldmann et al [1] note that cracking sensitivity is associated with particular details in the steelwork, e.g. at the end of steel beams with large depth, with this category including half-depth end plates, flame cut surfaces or flame cut surfaces with subsequent grinding or drilling of cope holes; in the vicinity of welds in thick plates; at the nodes of latticed structures, in particular those with hollow sections; and at drainage holes in corner areas. These regions of sensitivity correlate with the four factors identified by Kinstler [7] as necessary in his review of the cracking of steels during galvanizing. Figure 1 shows these four factors as a Venn diagram that identifies the critical intersection region for LMAC in red. The FAMEGA report [3] provides a useful Table identifying the factors that contribute to LMAC, drawn from the Kinstler document [7]. This table is duplicated below as Table 1 with some additions (shown in bold) from the experience of the present authors.

However, the data on Sn limits given in Table 1 appears to derive from a single study by Poag and Zervoudis [8], reported by Kinstler [7] in which the experimental work focused on the susceptibility to cracking of hollow structural steel tubing during galvanizing, and the crack response of pre-stressed steel specimens immersed in various molten zinc bath compositions. The hollow steel used by Poag and Zervoudis appears to be square section $\frac{3}{8}$ inch (9.5 mm) thick and the corner microstructures reproduced by Kinstler in his report demonstrate the

existence of small defects (up to 50 μm) on the inner surface of the corners. Kinstler notes that *“The findings of the study beyond those related to the smoothness of the inner corner surface and the heat treatment to reduce cracking incident are that alloy additions to the SHG Zinc bath did have an effect on the occurrence and severity of cracking, but only on susceptible tubes”*. Kinstler further notes that *“The central value of the study is to identify that galvanizing bath chemistry is only one of the factors influencing cracking of galvanized structural steels. The predominant variable has been found to be in the steel. For example, the presence of any alloy addition including tin up to 1.0% could not cause Tube B to crack. On the other hand, Tube A (in the absence of stress relieving) cracked under all bath chemistry variable conditions, including Special High Grade Zinc with no alloy additions.”*

Kinstler amplifies the importance of steel condition by stating that *“All of the many research programs which have studied hardness of flame-cut edges and their associated heat affected zones (HAZ), and cracking in molten zinc are in agreement that:*

- *There is a threshold hardness value above which the steel is susceptible to cracking in molten zinc.*
- *The threshold value is between about 250 and 300 HV (VHN) depending on the thickness of the steel, and possibly other steel-related variables.*
- *Re-attainment of a hardness below the threshold value, in previously harder steel reduces susceptibility of the steel to molten zinc cracking.”*

Experience in the UK has shown that the frequency of cracking of structural steel is very low, and that when it does occur it is almost invariably due to known factors that influence the propensity for weld cracking and that are also influential during the galvanizing process, e.g. distortion cracking, hydrogen embrittlement and strain age embrittlement [9]. In its conclusions, reference [9] observes that LMAC requires the presence of a susceptible steel alloy; a stress/strain concentration site (often already associated with pre-existing surface cracks); high levels of residual stress in the fabrication, developed for instance through rolling, finishing (at the steel mill), welding, hardened surfaces, movement of the fabricated elements, pre-treatment, galvanizing or forging, as well as the presence of molten zinc during the galvanizing operation. However, the first three of these factors also directly influence susceptibility to other cracking mechanisms associated with structural steelwork. The fourth factor may also indirectly enhance the potential for other forms of cracking of a structure through differential thermal expansion, which will depend on factors like structural component size and dipping speed. The net result of these various influences in particular and rare circumstances is that small, fine cracks may develop in a structural component prior to the hot dip galvanizing process and these may initiate further cracking during galvanizing.

However, to the best knowledge of the present authors, there has been no systematic attempt to examine, identify and record the possible presence and type of any pre-existing defects present in structural steelwork prior to the galvanizing process and their contribution to any cracking observed after galvanizing. With this in mind, a study of galvanizing of both general and structural steelwork was initiated to objectively establish the true risk of cracking for hot dip galvanized steel. The study was based on the UK experience where the risk of cracking is primarily controlled by the bath metallurgy and was intended to investigate whether the existing guidance is appropriate. It therefore did not address all the factors that are included in some European guidelines, e.g. DAST R022, and had the following aims:

- i) to establish the true frequency of cracking events during galvanizing.
- ii) to identify the causative factors underlying any observed cracking events.
- iii) to determine the number of such events that could be ascribed to LMAC.
- iv) to ascertain whether existing UK guidance on galvanizing remains appropriate.

This paper reports the results from this study of 1,011,458 tonnes of steel galvanized in various UK plants over a 5-year period, of which some 560,000 tonnes comprised structural steelwork (defined in this paper as covering building frames (including single and multi-storey and agricultural buildings), angles and flats for buildings, towers, masts, joists, and channels). The steelwork was subjected to high standards of visual inspection before and after galvanizing and the galvanizing conditions were inside the scope of the BCSA-GA guidance [5]. In this respect, all of the steel galvanized in this project was processed in galvanizing baths that used zinc melts complying with the limits set out in the BCSA-GA guidance, i.e. satisfying the criteria that:

$$\Sigma (\text{Sn} + \text{Pb}) \leq 1.3 \text{ wt\% and}$$

$$\text{Bi} \leq 0.1 \text{ wt\%}$$

The melt compositions used also fell inside the DAST R022 guidelines [4] for Class 1 standard zinc alloys given in Table 8 of that guide with $\text{Sn} \leq 0.1 \text{ wt\%}$. Traditionally, UK general galvanizing baths had been operated with tin at low levels anyway and so there was nothing new in this. As noted above, a higher tin limit of 0.30% is supported by the results obtained in recent work published by Carpio et al [6] who proposed a model for the failure micromechanisms of structural steels during hot-dip galvanizing.

2. Results

This investigation of more than one million tonnes of steel galvanized over 5 years supports the view expressed in references [4] and [10] that, when correctly implemented, current guidance on galvanizing structural steelwork leads to an extremely low incidence of cracking that can be attributed to LMAC. The other main conclusions from the present study are that:

- Only two instances (each involving one crack) were reported by the steelwork users that had not been previously found by inspection at the galvanizing plants.
- The overall cracked tonnage found by galvanizers was 0.033%. Note that this figure includes any cracks extending from pre-existing cracks that might not have been detected by either the fabricator or on arrival at the galvanizing plant.
- The cracked tonnage in the structural steelwork was 0.026% and that in the non-structural category was 0.043%. These data indicate that the risk of cracking in steelwork that was classified as structural was actually 40% lower than the risk for non-structural steelwork. This finding may reflect a higher or more consistent standard of fabrication in structural steelwork.
- The incidence of cracking in S355 grade structural steel was not observed to be any higher than that in S275 grade steel.

- Particularly notable was the lack of practical evidence to support the high level of focus within DAST R022 placed on beam section height in determining risk characterisation and control criteria, as a basis of ranking. Within the whole of this project during which beams were routinely galvanised in depths up to 1.5 m, there was not a single case of cracking regardless of the end detail. This risk is heavily emphasised in the JRC report with a photograph showing severe longitudinal cracking in a beam, leading to the conclusion that there is a significant risk. This was not proven by events during this project lasting more than five years.

In this study, most of the rare cracking events found were related to controllable design or fabrication issues and the small number of problems discovered were all repairable. Importantly, there were no reports of any cracks being observed under the galvanized coating and it was clear that LMAC was not an issue in galvanizing baths with tin (Sn) contents and melts that comply with the BCSA-GA guidance [4].

In addition, a more detailed analysis of cracking events was carried out during the last two years of the project. During this period, there were 102 instances of cracking that occurred during the galvanizing process, involving 219 cracks in 127 tonnes of steelwork, with 46 events (45%) classified as occurring in structural steelwork and 56 (55%) as non-structural. The average weight of cracked components was 0.58 tonnes with 19 weighing ≤ 0.10 tonnes and 33 weighing > 1 tonne. This figure of 127 tonnes represents 0.032% of the total galvanized steelwork over 2 years (395,000 tonnes). Within these data, the highest number of cracking instances occurred in rectangular or square hollow sections (48 events) with rolled-steel joists comprising the second highest category (26 events) and rolled channels the third (17 events). A very high level of correlation between cracking and welded details was observed, with 177 cracks being associated with welds. Many of the cracks identified prior to galvanizing were also associated with welds, and the total number where there was an identified sub-standard of fabrication issue was 56 out of the total of 102.

Table 2 summarises the crack locations observed in this more detailed two-year analysis of cracking. It is worth noting that only 5% of the cracks associated with either weld zones or parent steel could be assigned solely to LMAC, i.e. with no likely precursor crack existing before the galvanizing process was carried out. In this respect it is important to note that such cracks were identical to those otherwise associated with weld defects and this study leads to the conclusion that LMAC should not be described as a root cause of cracking during galvanizing, but rather as a factor in further crack propagation where an incipient crack-like defect or crack-susceptible region already exists.

Equally, the study found no correlation between risk of cracking and the size or weight of the steelwork being galvanized, with the contributory factors for the observed occasional cracking being uniform across all steelwork. However, as noted in reference [9], where cracking is associated with welds that are coincident with high level of residual stresses, e.g. the termination of end-plates on large I-beams, or with certain cold-rolled hollow sections, then increasing component size is likely to lead to increased levels of residual stress and the risk of cracking is therefore higher.

The remaining sections of the present paper will present an outline and categorisation of the various types of crack observed.

3. Examples of Cracking Detected Before Galvanizing

The types of crack identified as existing after fabrication were usually related to detail types with known susceptibility to cracking, and can hence usually be ascribed to sub-optimum design. Figure 2 shows one example of such cracking associated with a tubular insert in a hollow section, where the weld run is too close to the edge of the component and the welding-induced residual stresses have combined with those existing from the fabrication at the corner of the hollow section to initiate cracking. Figure 3 shows another example of cracking that occurred during fabrication arising from the superposition of welding residual stress and hardness gradients with other pre-existing fabrication stresses. Figure 4 shows cracking observed in steel checker or tread plate, which is more susceptible to cracking during bending than a plane component because of the raised tear drop shapes. If the usual minimum bend radius is perhaps $1.5t$, where t is the plate thickness, then checker plate would require a larger inner radius of at least $3t$.

4. Examples of Steelwork Susceptible to Cracking During Galvanizing

Figure 5 shows an interesting example of cracking that occurred during galvanizing and that is similar to a cope hole. A weld crack has initiated at a cut-out intended to avoid the defect-prone intersection of multiple welds. Cope holes and 'snipes', i.e. vent or drain holes and openings, are a common cause of cracking problems during fabrication and galvanizing and Figure 6 shows fabrication cracking induced at flame-cut snipe that was introduced to facilitate making a multipass weld. This crack would generally be ascribed to LMAC, rather than having its root cause as poor fabrication practice.

Complex welded fabrications involving the joining of plates of significantly different thickness can lead to cracking during galvanizing because of the differential cooling rates, hardness values and stress concentrations associated with such joints. Figure 7 shows one such example where discussions between the fabricator and the galvanizer would have enabled a minor change to fabrication to be made, perhaps utilising bolting together of the two assemblies, and the problem would have been eliminated. Figure 8 illustrates another problem sometimes encountered during galvanizing of relatively heavy and complex welded fabrications. The square box section shown in Figure 8b has welds coincident with regions of high residual stress at high constraint corners. The interplay among geometric stress concentrations, hardness gradients and residual stresses can very easily either initiate micro-cracks that extend during galvanizing, or initiate LMAC in the galvanizing bath (Figure 8c). Possible design changes that could be implemented to avoid this problem include the use of hot formed seamless tube.

The stresses induced in highly constrained steelwork can combine with poor welding practice, such as partial penetration, to create cracking problems during galvanizing. Figure 9 shows one example of this where partial weld penetration and subsequent weld grinding have led to cracking. A number of instances of cracking arising from insufficient weld thickness as a result of weld dressing and/or partial penetration were observed in other components during this investigation into galvanizing of steelwork.

High levels of distortion-induced stresses can occur during galvanizing and an example of cracking induced by distortion is shown in Figure 10, where distortion in a smaller and highly constrained member has combined with additional stress localisation at an off-centre hole to initiate cracking. Distortion of members can also occur due to inadequate venting in steelwork intended for galvanizing. This problem is illustrated in Figure 11, where smaller and properly vented members were welded onto a larger section that was not adequately vented. Trapped internal gases have led to local bulging of the main member in the thermally-affected weld zone and hence initiated cracking at its junction with the cross-members.

As a final example of the range of problems sometimes experienced during galvanizing, Figure 12 shows cracking in a cold formed rectangular hollow section. The residual stresses induced in either cold-rolled or welded hollow sections at the corners, tend to increase with increase in length of the component. Cracking can initiate or extend during galvanizing from either small defects at the weld ends or local stress concentrations/hard spots at flame cut edges. The high levels of tensile residual stress that existed in the outer surface are evidenced in the deformation seen in the plate after cracking.

5. Conclusions

This review of cracking events observed either after fabrication or after hot dip galvanizing, in >1,000,000 tonnes of steelwork with 560,000 tonnes falling into a structural classification, has unequivocally demonstrated that such occurrences are extremely rare. The total overall cracked tonnage was found to be 0.033%, with 0.026% of the structural steel tonnage having cracks and 0.043% of the non-structural category containing cracks. A visual investigation of the observed cracking events, as described in this paper, further indicated that the large majority of cracks were associated with weld zones.

The underlying causes of cracking fell into well-known categories of sub-optimum design, involving either weld details or design for galvanizing, many of which have already been described in more detail in reference [9]. This work supports two important conclusions, firstly, that LMAC cannot accurately be described as a root cause of cracking during galvanizing, but is rather a factor in further crack propagation where an incipient crack-like defect or crack-susceptible region already exists in the steelwork to be galvanized; and, secondly, that LMAC is not an issue when using galvanizing baths with tin (Sn) contents and melts that comply with the BC-SA-GA guidance [5]. Finally, it is clear that liaison with the galvanizing plants during the design process would eliminate a number of potential cracking problems that can arise from sub-optimum design for the galvanizing process.

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Tensile Stress	Specific Material Condition	Liquid Metal
Stress concentration (especially welds)	Strength/hardness > 250-290 HV Hydrogen cracking <ul style="list-style-type: none"> Pickling and fluxing of high strength steels Flux containing Fe > 10 g/l Weld regions with HV > 300-350 	Pb: increases incidence and severity of cracking
Residual stress <ul style="list-style-type: none"> Straightening Thermal cutting Welding Cold work 		Ni: No effect
Thermal stress <ul style="list-style-type: none"> Component size Dipping speed and angle 		Sn and Bi > 0.2% increases crack size
		Sn > 0.3% increases crack size

Table 1 Factors contributing to the occurrence of liquid metal assisted cracking LMAC. After Kinstler [7] and as given in reference [3]. Factors in bold are additions added by the authors.

Location of Crack	%	% LMAC
Cope hole cut-out and other design issues	10	0
Steel plate, e.g. distortion or material defect	12	5
Weld zone	78	

Table 2 Proportion of cracks found in the final 2-year analysis of galvanized steelwork in terms of their location and the percentage considered to involve LMAC.

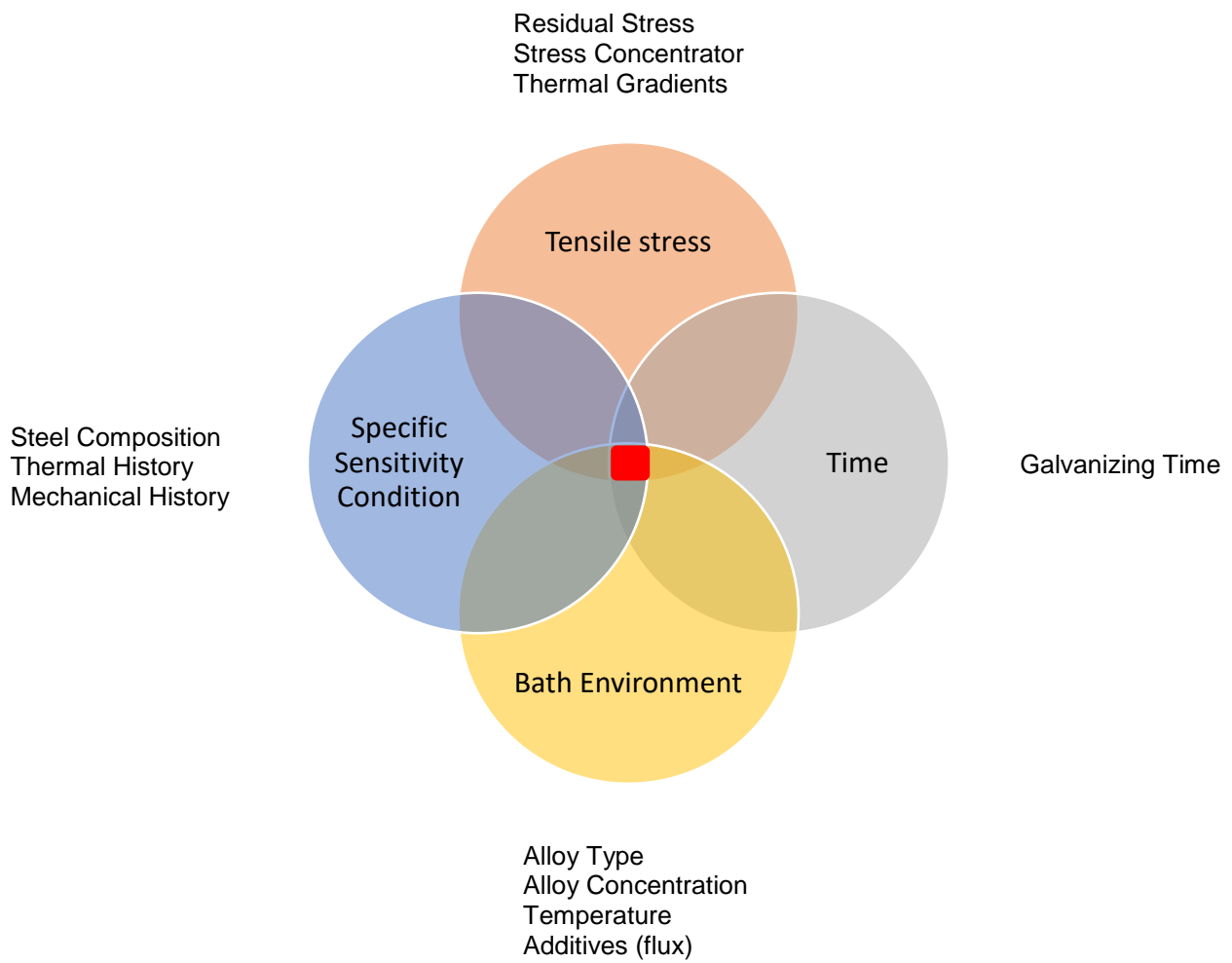


Figure 1 Venn diagram showing the critical intersection region (red) of the four necessary conditions defined by Kinstler [7] for the occurrence of LMAC during galvanizing.

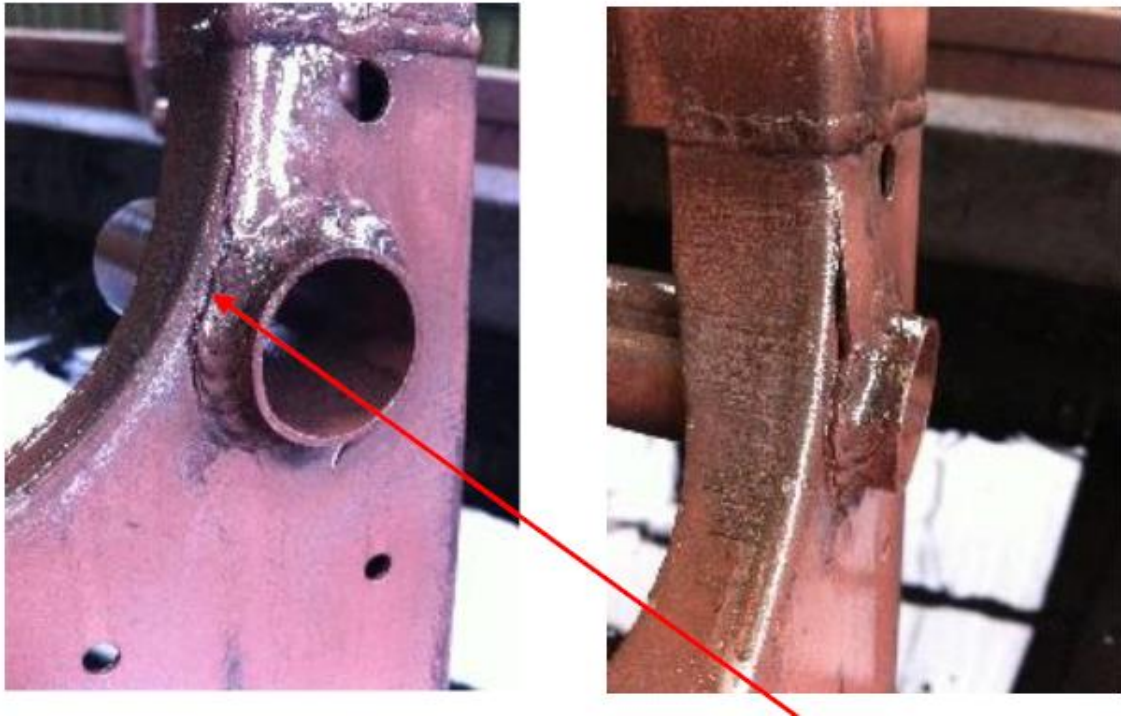
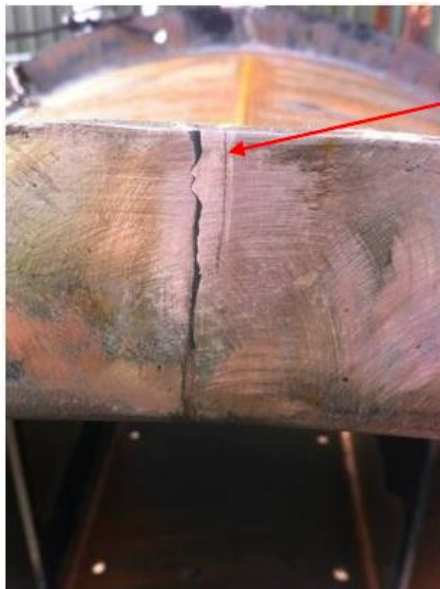


Figure 2 Weld run around an insert that was too close to an existing fabrication-induced region of plasticity/residual stress.



Small hairline crack in
flange of casing near weld



Figure 3 This crack is probably again due to a combination of the welding process (residual stress and hardness gradients) and the stresses induced during forming of the cylindrical casing.



Figure 4 The cracking seen here is due to the steel checker plate having too tight a bend radius.



Figure 5 Weld cracking initiated from a small cut-out intended to avoid the problem of intersecting welds in fabrication of a hollow section.



Figure 6 A crack that has initiated at a flame-cut 'snipe' intended to facilitate making a multipass weld. Cracking is due to the high local hardness and stress concentrations induced during flame cutting.



Figure 7 Cracking at the highly constrained joint between a smaller sub-assembly and a large I-beam. Separate fabrication of the two components and subsequent bolting would have eliminated the problem.



Figure 8 The complex fabrication shown in a) has square box sections b) where several welds are coincident at the highly constrained corners. The interplay among geometric stress concentrations, hardness gradients and residual stresses can very easily either initiate micro-cracks that extend during galvanizing, or initiate LMAC in the galvanizing bath

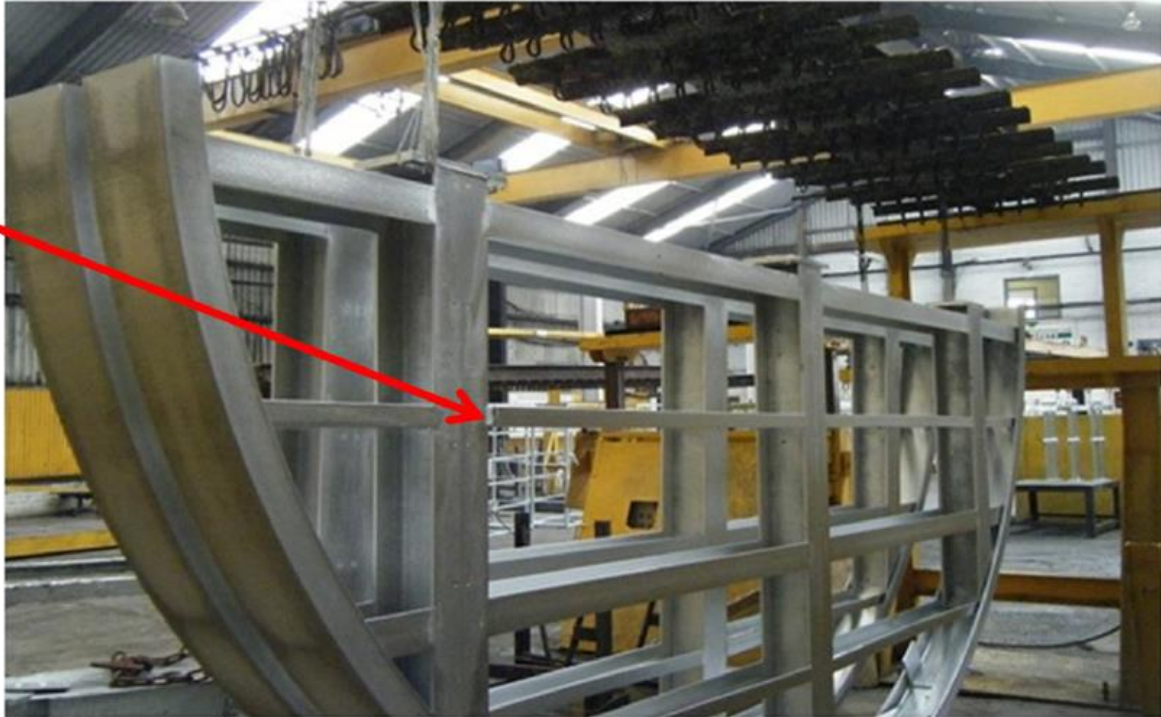


Figure 9 In this complex welded fabrication, partial weld penetration and subsequent weld grinding have led to cracking occurring during galvanizing from the under-sized weld.



Figure 10 Significant distortion has occurred in the highly constrained smaller cross-members in this steel fabrication, and the off-centre hole has led to an additional localisation of stress, causing cracking to occur during galvanizing.



Figure 11 Inadequate venting provision has led to bulging of the main member in the thermally weakened zone where the cross-members were welded to it, causing cracking.



Figure 12 Cracking in a cold formed steel section that has initiated from one end due to the high levels of residual stresses existing in the cold formed section at the corners.